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(54) **STREAMING LIGHT PROPAGATION**

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None
See application file for complete search history.

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(57) **ABSTRACT**

A method is provided for streaming light propagation with particular application for feature films and other demanding content creation using scenes of high complexity requiring art directed global illumination. By attaching a data recording shader or equivalent functionality to any tracing based renderer that can provide multi-pass global illumination, the complete set of light bounce propagation records and the set of emissive samples for a particular rendering can be recorded to memory or disk. A user may edit the emissive samples to adjust the lighting environment, including modifying light source color and intensity and even moving and adding new emissive samples. To relight the scene, the edited emissive samples are processed through the propagation records using a streaming multiply-and-add operation amenable to high levels of parallelization, avoiding a costly re-rendering of the scene and providing a final quality result in interactive time.

20 Claims, 3 Drawing Sheets

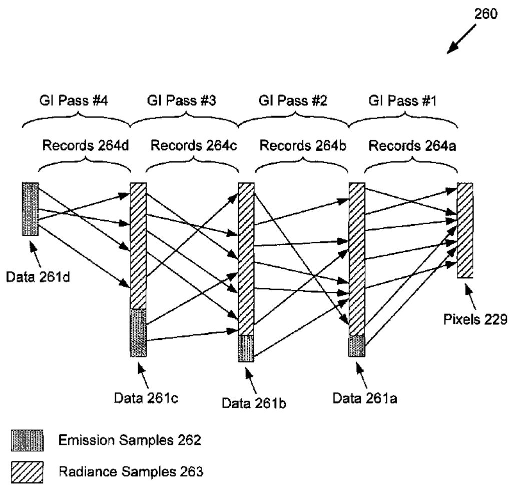

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Fig. 1

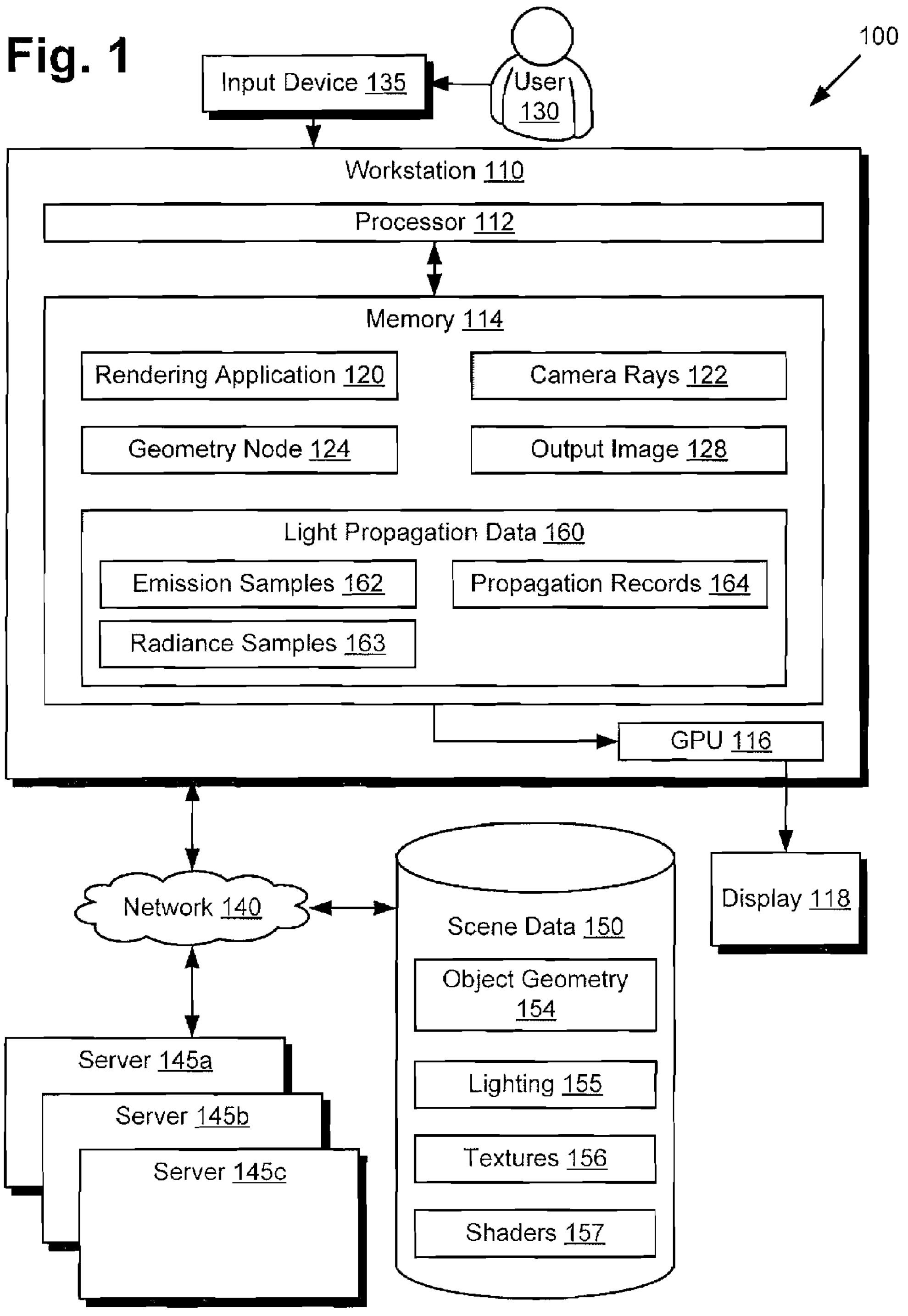

100
Input Device 135
User 130
Workstation 110
Processor 112
Memory 114
Rendering Application 120
Camera Rays 122
Geometry Node 124
Output Image 128
Light Propagation Data 160
Emission Samples 162
Propagation Records 164
Radiance Samples 163
GPU 116
Network 140
Scene Data 150
Object Geometry 154
Lighting 155
Textures 156
Shaders 157
Display 118
Server 145a
Server 145b
Server 145c

Fig. 2

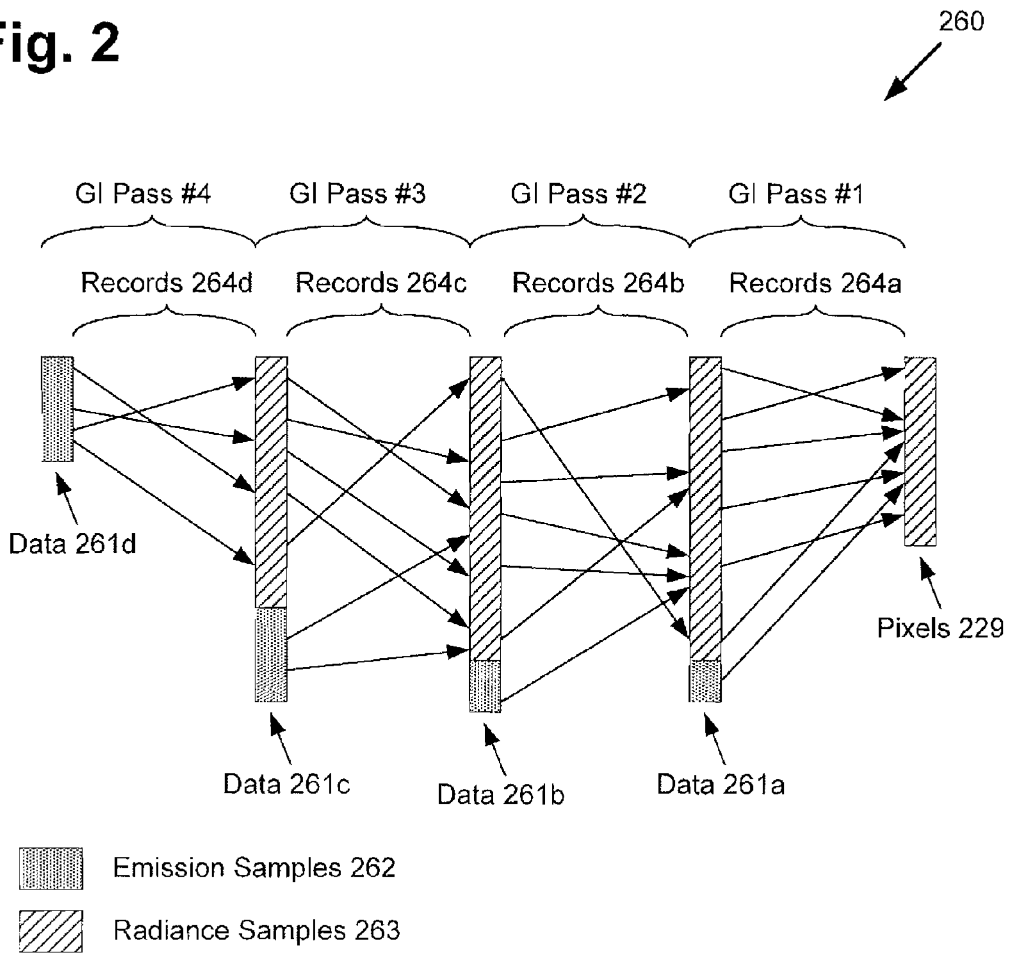
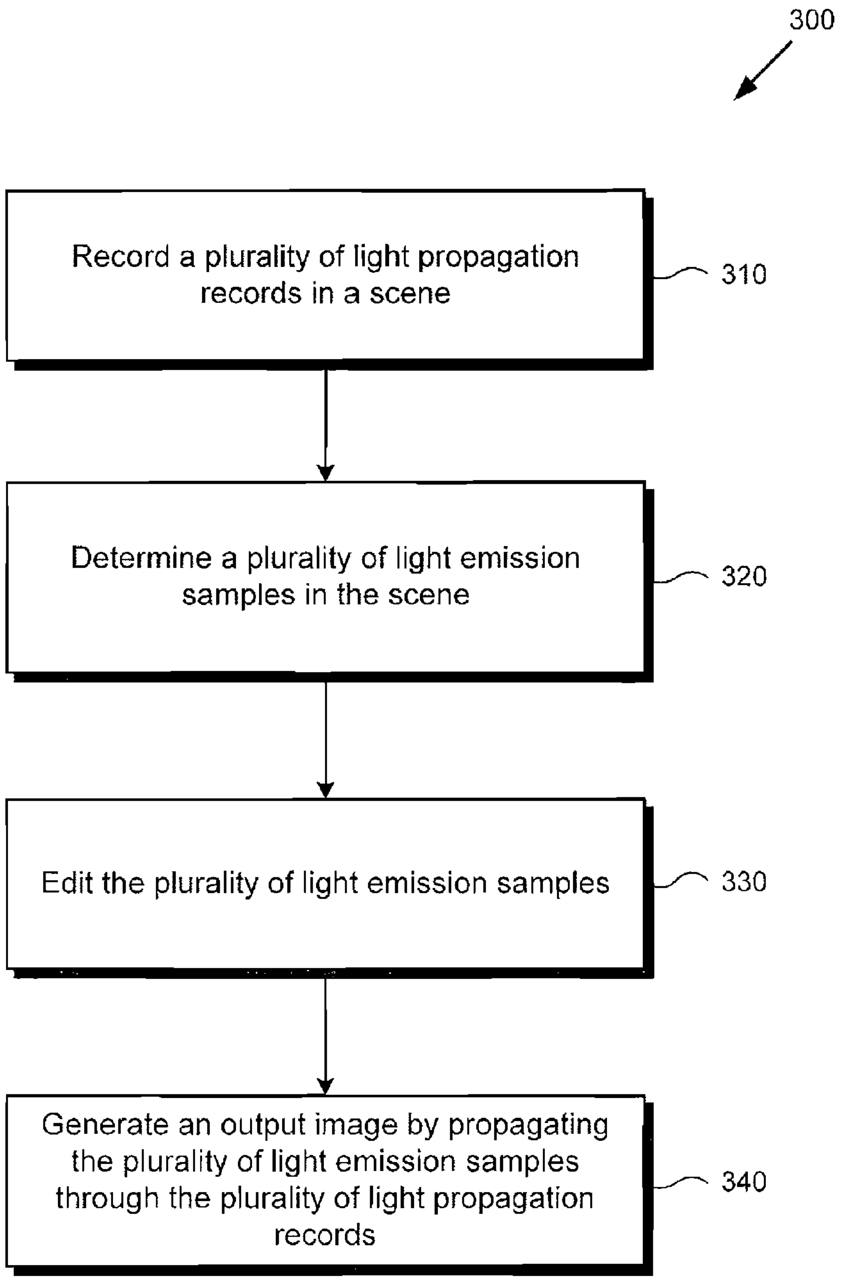

260
GI Pass #4
GI Pass #3
GI Pass #2
GI Pass #1
Records 264d
Records 264c
Records 264b
Records 264a
Data 261d
Data 261c
Data 261b
Data 261a
Pixels 229
Emission Samples 262
Radiance Samples 263

Fig. 3


300
Record a plurality of light propagation records in a scene
310
Determine a plurality of light emission samples in the scene
320
Edit the plurality of light emission samples
330
Generate an output image by propagating the plurality of light emission samples through the plurality of light propagation records
340

STREAMING LIGHT PROPAGATION

BACKGROUND

Realistic lighting is an important component of high quality computer rendered graphics. By utilizing a renderer employing a global illumination model, scenes can be provided with convincing reflections and shadows, providing the requisite visual detail demanded by feature length animated films and other content. Conventionally, a ray tracing renderer may be utilized to provide global illumination in a simple manner.

SUMMARY

The present disclosure is directed to streaming light propagation, substantially as shown in and/or described in connection with at least one of the figures, as set forth more completely in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** presents an exemplary diagram of a system for providing streaming light propagation;

FIG. **2** presents an exemplary diagram of a data structure for light propagation data; and

FIG. **3** presents an exemplary flowchart illustrating a method for providing streaming light propagation.

DETAILED DESCRIPTION

The following description contains specific information pertaining to implementations in the present disclosure. One skilled in the art will recognize that the present disclosure may be implemented in a manner different from that specifically discussed herein. The drawings in the present application and their accompanying detailed description are directed to merely exemplary implementations. Unless noted otherwise, like or corresponding elements among the figures may be indicated by like or corresponding reference numerals. Moreover, the drawings and illustrations in the present application are generally not to scale, and are not intended to correspond to actual relative dimensions.

With large processing overhead and highly random data access requirements, ray tracing becomes less suitable for complex scenes with larger amounts of data, as required by feature films and other challenging applications. Moreover, to provide lighting environments that are artistically driven and visually attractive, artists and directors require interactive visualization of lighting changes. A conventional ray tracer requires the entire scene to be re-rendered again to show the result of any lighting changes, a time consuming and resource intensive process that may not be reasonably accommodated within a production budget. While techniques such as renderer state caching and screen-space data structures may assist in accelerating the re-rendering process, such approaches are often only limited to specific portions of the scene and can only provide a lower quality visualization compared to a final quality rendering.

Accordingly, FIG. **1** presents an exemplary diagram of a system for providing streaming light propagation. Diagram **100** of FIG. **1** includes workstation **110**, display **118**, user **130**, input device **135**, network **140**, servers **145***a*, **145***b* and **145***c*, and scene data **150**. Workstation **110** includes processor **112**, memory **114**, and graphics processing unit (GPU) **116**. Memory **114** includes rendering application **120**, camera rays **122**, geometry node **124**, output image **128**, and light propagation data **160**. Light propagation data **160** includes emission samples **162**, radiance samples **163**, and propagation records **164**. Scene data **150** includes object geometry **154**, lighting **155**, textures **156**, and shaders **157**.

Workstation **110** may be any computing device such as a rackmount server, desktop computer, or mobile computer. User **130** may utilize input device **135**, for example a keyboard and mouse, to direct the operation of rendering application **120** executing in memory **114** of processor **112**. Rendering application **120** may process scene data **150** received from network **140** to generate a rendered output image **128** for output to display **118** through GPU **116**. Network **140** may be a high speed network suitable for high performance computing (HPC), for example a 10 GigE network or an InfiniBand network. Once completed, output image **128** may also be copied to non-volatile storage, not shown in FIG. **1**.

For simplicity, it is assumed that output image **128** is only a single frame and that object geometry **154** already includes the positioning of all objects within the scene for the associated frame. However, in alternative implementations, scene data **150** may further include motion data for object geometry **154**, in which case several animation frames may be rendered by rendering application **120**. Moreover, some implementations may render multiple frames of the same scene concurrently, for example to provide alternative camera angles or to provide stereoscopic rendering. Lighting **155** may include the properties of all light sources within the scene. Textures **156** may include all textures necessary for object geometry **154**. Shaders **157** may include any shaders necessary to correctly shade object geometry **154**. Other data may also be stored in scene data **150**, for example virtual camera parameters and camera paths.

As previously discussed, it is desirable to provide realistic lighting for a computer generated graphics rendering, or output image **128**. While rasterizing renderers can provide high performance, global illumination can only be approximated. For demanding applications such as feature film rendering, high quality global illumination is required from rendering application **120**.

Accordingly, rendering application **120** is any type of renderer that can provide high quality global illumination, such as a ray tracing based renderer. For example, rendering application **120** may be a streaming global illumination renderer, where all the camera rays **122** necessary for rendering output image **128** are generated and kept within memory **114**. Object geometry **154** is streamed into memory **114** as individual work units or nodes, with an exemplary geometry node **124** as shown, processed against camera rays **122** using other elements of scene data **150** as desired, and freed from memory **114**. Since all required processing is completed after freeing the node from memory, each geometry node **124** of object geometry **154** needs to be accessed at most once, and may also be skipped if the geometry node is not visible in the current scene. The above streaming of object geometry **154** is repeated for as many global illumination passes as required, for example 2-4 passes. Since performing only one pass is equivalent to ray casting, at least two passes are required in one configuration.

Since each geometry node **124** is an individual work unit and can be processed without dependencies from other geometry nodes, servers **145***a*, **145***b*, and **145***c* may also be utilized for distributed parallel processing. Servers **145***a*, **145***b*, and **145***c* may contain components similar to those of workstation **110**. SIMD (single instruction, multiple data) instructions on processor **112** and shaders on GPU **116** may be utilized to further enhance parallelism. Hierarchical traversal across camera rays **122** and object geometry **154** may also be utilized to reduce the number of intersection comparisons required.

While high quality global illumination can be provided by using a ray tracing based renderer for rendering application **120**, interactive visualization of lighting changes is still difficult to provide since scene data **150** must be re-rendered if lighting **155** is modified. Since the re-rendering process requires significant time and resources, artists and directors cannot quickly visualize different lighting configurations for optimizing artist-directed lighting in a scene. While some techniques are applicable to accelerate the re-rendering process, such techniques often only affect limited portions of the scene and can only provide a lower quality visualization compared to a final quality rendering.

Accordingly, the recording of light propagation data **160** is proposed for rendering application **120**. While rendering application **120** is tracing output image **128** for the first time, the light propagation records of camera rays **122** are recorded as propagation records **164** within light propagation data **160**. Additionally, all emission samples and radiance samples are tracked and stored as emission samples **162** and radiance samples **163**, respectively. While camera rays are utilized in FIG. **1** for simplicity, alternative embodiments may also use camera cones or other shapes for cone tracing or other shape tracing. Intermediate sums for each pass of a multi-bounce global illumination rendering may also be stored within light propagation data **160** for filtering between bounces.

When emission samples **162** and therefore lighting **155** is adjusted, then output image **128** can be reconstructed by streaming emission samples **162** through propagation records **164**, bypassing a re-rendering of scene data **150**. Relighting of scene data **150** can therefore be carried out orders of magnitude faster than a straightforward re-rendering. Since the streaming of emission samples **162** through propagation records **164** is essentially a streaming multiply-and-add operation amenable to parallel processing rather than a recursive algorithm, rendering application **120** can relight at interactive rates by utilizing parallelism available to processor **112** and/or GPU **116**, allowing artists and directors to immediately visualize lighting changes in full final rendering quality.

For example, assuming a target render size of approximately 2 megapixels for high definition or Full HD (1920 by 1080) video, and assuming a desired sampling of 100 samples per pixel to provide sufficient data for filtering, approximately 200 million propagation records are required per global illumination bounce pass. Assuming each record occupies 20 bytes and assuming four (4) global illumination bounce passes, approximately 16 gigabytes of memory is required from memory **114**, an amount easily allocated for a modern server or even a high-end consumer class desktop computer. If insufficient memory is available, high speed local storage such as solid state disks and/or RAID arrays may also be utilized.

FIG. **2** presents an exemplary diagram of a data structure for light propagation data. Light propagation data **260** of FIG. **2** includes data **261***a*, **261***b*, **261***c*, and **261***d*, which include emission samples **262**, radiance samples **263**, records **264***a*, **264***b*, **264***c*, and **264***d*, and pixels **229**. With respect to FIG. **2**, light propagation data **260** may correspond to light propagation data **160** from FIG. **1**. Emission samples **262** may correspond to emission samples **162** from FIG. **1**. Pixels **229** may correspond to pixels of output image **128** of FIG. **1**. It should be noted that the depiction of light propagation data **260** in FIG. **2** is only a schematic simplification as each data set and record group may potentially contain hundreds of millions of records.

Light propagation data **260** shows an exemplary recording from four (4) global illumination bounce passes. Accordingly, data **261***d* corresponds to samples from a fourth pass, data **261***c* corresponds to samples from a third pass, data **261***b* corresponds to samples from a second pass, and data **261***a* corresponds to samples from a first pass. Data **261***d* contains only emission samples **262** as data **261***d* corresponds to samples from a final global illumination bounce pass. More specifically, since no further bounces are generated on the final pass, all samples must be emissive by definition since they do not rely on other samples. Data **261***c*, **261***b*, and **261***a* may each include a mix of emission samples **262** and radiance samples **263**, as shown. Finally, pixels **229**, which may correspond to pixels of a final output image **128**, includes only radiance samples **263**, as the pixels must be derived from the tracing.

Rendering application **120** can record light propagation data **160** including emission samples **162** as emission samples **262** and propagation records **164** as records **264***a*, **264***b*, **264***c*, and **264***d*. The remaining radiance samples **263** can be derived from this minimal data set. However, to support filtering between bounces, the intermediate sums from radiance samples **263** may be optionally recorded as well. To implement the recording of light propagation data **160** in rendering application **120**, shaders **157** may include a data recording shader executed for each bounce of camera rays **122** in rendering application **120**, thereby recording light propagation data **160** while generating output image **128**.

More specifically, each of emission samples **262** and radiance samples **263** may correspond to a record containing a color value, such as a red, green, blue (RGB) value. Records **264***a*-**264***d* may associate source points and destination points in scene data **150** to emission samples **262** or radiance samples **263**. The records may also be segmented according to the associated global illumination (GI) bounce pass. For example, data **261***d* and records **264***d* may be segmented into a data structure corresponding to GI pass #**4**, whereas data **261***a* and records **264***a* may be segmented into another data structure corresponding to GI pass #**1**, as shown. The segmentation may be implemented in the data recording shader, as discussed above.

To improve data coherency for multiple relighting operations, data **261***a*, **261***b*, **261***c*, and **261***d* may be sorted, for example by source point or destination point. Since a large number of records may need to be sorted, GPU **116** may be utilized for accelerated sorting. For example, the high performance RadixSorting algorithm can sort over 1G keys per second on a modern CUDA compatible GPU. See, "RadixSorting, High performance GPU radix sorting in CUDA", available from http://code.google.com/p/back40computing/wiki/RadixSorting.

FIG. **3** presents an exemplary flowchart illustrating a method for providing streaming light propagation. Flowchart **300** begins when processor **112** of workstation **110** records propagation records **164** in a scene represented by scene data **150** (block **310**). As previously discussed, this may be carried out by attaching a data recording shader within shaders **157**, causing rendering application **120** to update propagation records **164** as camera rays **122** are bounced in the scene rendering. Rendering application **120** may also be directly modified to record propagation records **164**. As previously discussed, as long as rendering application **120** is based on a tracing renderer providing high quality global illumination, any suitable renderer may be utilized, including cone tracers and others. After the rendering is finished, the recorded propagation records **164** may appear similar to records **264***a*-**264***d* as shown in light propagation data **260** of FIG. **2**. As previously discussed, the recording of the propagation records may also be segmented according to GI bounce pass, and the records may be sorted by source or destination index for improved data coherency.

Next, processor **112** of workstation **110** determines emission samples **162** in scene data **150** (block **320**). Turning to FIG. **2**, this is equivalent to determining emission samples **262**. For example, the data recording shader may be further configured to also update emission samples **162** if an intersection sample requires no further bounces, indicating a light emission sample. As previously discussed, radiance samples **263** may also be recorded by the data recording shader to assist in filtering between bounces. Similar to the propagation records, the data samples may also be segmented according to GI bounce pass, as shown in FIG. **2**.

Next, processor **112** of workstation **110** edits emission samples **162**, corresponding to emission samples **262** in FIG. **2** (block **330**). For example, rendering application **120** may present a graphical user interface on display **118**, allowing user **130** to adjust the lighting via input device **135**. Thus, user **130** may modify emission samples **262**, for example by changing light intensity and/or RGB color values. User **130** may even move or add new light sources to emission samples **262**, as long as the new or moved light sources do not require absorbing or scattering that would invalidate the other existing records **164**. To accommodate any newly updated or added light sources in emission samples **262**, light propagation records **164** may be intersected with emissive geometry in scene data **150** to determine all responsive record updates for propagation records **164**. Accordingly, user **130** can flexibly adjust the lighting of the scene to produce art driven lighting effects.

Additionally, user **130** can flexibly generate effects, mattes, and arbitrary output variables (AOVs) by selecting specific paths for modification. As non-limiting examples, paths intersecting with particular objects or geometry, paths hitting particular light sources, and paths within a specific global illumination pass may be targeted. Since all possible paths are recorded in propagation records **164**, the selection of specific paths for mattes and AOVs is greatly facilitated. Further, user **130** can specify radiance filters applied to selected paths that may adjust radiance values for specific regions of scene data **150**. For example, a color correction or color conversion filter may be provided to modify radiance values for a specific object.

Next, processor **112** of workstation **110** generates output image **128** containing pixels **229** by propagating the edited emission samples **162**, corresponding to emission samples **262**, through propagation records **164**, or records **264***a*-**264***d* (block **340**). Example pseudocode is as follows:

```
Initialize array D with edited emission samples;
For (I = last GI pass; I--; I > 0) {
  For each record R in segmentation P[I] {
    D[R.destinationIndex][I-1] += D[R.sourceIndex][I]
                * R.amount;
}}
```

Using light propagation data **260** from FIG. **2** as an example, the above pseudocode would first begin by initializing an array D with emission samples **262**, as edited by user **130**. This step would already be completed in steps (**320**) and (**330**) above. For simplicity, an array D is assumed that has sufficient memory allocation for all possible samples in the scene; however, an actual implementation may use sparse arrays, linked lists, tree hierarchies, hash tables, and/or other data structures. The remaining values in array D, which include values to be populated with radiance samples **263**, are initialized to a default value, such as zero.

The outer loop iterates from the last GI pass to the first GI pass. Thus, the GI pass index I begins at GI Pass #**4** (last GI pass) and decrements (I–) until GI pass #**1** is processed (I>0), after which the loop finishes. The inner loop iterates through each record R within the present segmentation P[I]. For example, since index I begins at GI Pass #**4**, the inner loop may first begin by processing each record R in segmentation P[4], or records **264***d* in FIG. **2**.

The processing for a particular record R proceeds by retrieving the RGB color value for the source point in R (D[R.sourceIndex][I]), multiplying it by the percentage indicated by the propagation amount in R (R.amount), and adding the result to the RGB color value for the destination point in R (D[R.destinationIndex][I−1]). As shown in FIG. **2**, D[R.sourceIndex][I] refers to values in data **261***d*, whereas D[R.destinationIndex][I−1] refers to values in data **261***c*. Note that the use of the += operator preserves any existing value that may be at the destination, since multiple records may accumulate to the same destination.

Since there are no data dependencies, and since writes to the same destination are easily resolved by simple addition, the streaming multiply-and-add operation of the inner loop in the above pseudocode algorithm is highly amenable to parallelism available to processor **112**, GPU **116**, and servers **145***a*-**145***c*, allowing for fast calculation of pixels **229** in interactive time. Thus, user **130** is enabled to adjust, move, or add to emission samples **162** and quickly observe the resulting lighting changes to output image **128**, which may be shown on display **118**. Advantageously, the relighting of output image **128** can be provided at full final render quality and automatically accounts for all possible lighting effects supported by rendering application **120**. Alternatively, to provide even faster results for real-time or near real-time feedback, rendering quality may be reduced using approximations or smaller data sets.

From the above description it is manifest that various techniques can be used for implementing the concepts described in the present application without departing from the scope of those concepts. Moreover, while the concepts have been described with specific reference to certain implementations, a person of ordinary skill in the art would recognize that changes can be made in form and detail without departing from the spirit and the scope of those concepts. As such, the described implementations are to be considered in all respects as illustrative and not restrictive. It should also be understood that the present application is not limited to the particular implementations described herein, but many rearrangements, modifications, and substitutions are possible without departing from the scope of the present disclosure.

What is claimed is:

1. A computing device for providing streaming light propagation, the computing device comprising:

a processor configured to:

record a plurality of light propagation records in the scene;

determine a plurality of light emission samples in the scene;

edit the plurality of light emission samples by changing at least one of light intensity and red, green, blue (RGB) color values to provide a plurality of edited light emission samples;

generate an output image by propagating the plurality of edited light emission Samples through the plurality of light propagation records, wherein the plurality of light propagation records each includes a source point and a destination point associated with emissive and radiance samples in the scene.

2. The computing device of claim **1**, wherein the editing of the plurality of light emission samples further intersects the plurality of light propagation records with emissive geometry in the scene to determine updates to the plurality of light propagation records in response to an adding or a moving of the plurality of light emission samples.

3. The computing device of claim **1**, wherein the processor is further configured to generate a matte or an arbitrary output variables (AOV) by selecting specific paths in the plurality of light propagation records.

4. The computing device of claim **1**, wherein the processor is further configured to apply a radiance filter to selected paths of the plurality of light propagation records.

5. The computing device of claim **1**, further comprising a memory, wherein the processor is configured to record the plurality of light propagation records in the memory.

6. The computing device of claim **1**, wherein the processor is further configured to show the output image on a display.

7. The computing device of claim **1**, wherein the propagating is by a streaming multiply-and-add operation.

8. A method for providing streaming light propagation for use by a computing device having a processor, the method comprising:

recording, by the processor, a plurality of light propagation records in a scene;

determining, by the processor, a plurality of light emission samples in the scene;

editing, by the processor, the plurality of light emission samples by changing at least one of light intensity and red, green, blue (RGB) color values to provide a plurality of edited light emission samples;

generating, by the processor, an output image by propagating the plurality of edited light emission samples through the plurality of light propagation records, wherein the plurality of light propagation records each includes a source point and a destination point associated with emissive and radiance samples in the scene.

9. The method of claim **8**, wherein the editing of the plurality of light emission samples further intersects the plurality of light propagation records with emissive geometry in the scene to determine updates to the plurality of light propagation records in response to an adding or a moving of the plurality of light emission samples.

10. The method of claim **8**, further comprising:

generating a matte or an arbitrary output variables (AOV) by selecting specific paths in the plurality of light propagation records.

11. The method of claim **8**, further comprising:

applying a radiance filter to selected paths of the plurality of fight propagation records.

12. The method of claim **8**, wherein the recording of the plurality of light propagation records is into a memory.

13. The method of claim **8**, further comprising:

showing the output image on a display.

14. The method of claim **8**, wherein the propagating is by a streaming multiply-and-add operation.

15. A system for providing streaming light propagation, the system comprising:

a display;

a computing device comprising a memory and a processor configured to:

record, in the memory, a plurality of light propagation records in a scene;

determine a plurality of light emission samples in the scene;

edit the plurality of light emission samples by changing at least one of light intensity and red, green, blue (RGB) color values to provide a plurality of edited light emission samples;

generate an output image for showing on the display by propagating the plurality of edited light emission samples through the plurality of light propagation records, wherein the plurality of light propagation records each includes a source point and a destination point associated with emissive and radiance samples in the scene.

16. The system of claim **15**, wherein the editing of the plurality of light emission samples further intersects the edited plurality of light emission samples with the scene to update the plurality of light propagation records, enabling an adding or a moving of the plurality of light emission samples.

17. The system of claim **15**, wherein the processor is further configured to generate a matte or an arbitrary output variables (AOV) by tracking specific paths in the plurality of light propagation records.

18. The system of claim **15**, wherein the processor is further configured to apply a radiance filter to selected paths of the plurality of light propagation records.

19. The system of claim **15**, wherein the processor is further configured to show the output image on the display.

20. The system of claim **15**, wherein the propagating is by a streaming multiply-and-add operation.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO.	: 9,053,582 B2	Page 1 of 1
APPLICATION NO.	: 13/493948	
DATED	: June 9, 2015	
INVENTOR(S)	: Burley et al.	

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the claims,

Column 6, line 57, claim 1, "records in the scene;" should be changed to --records in a scene;--

Column 6, line 66, claim 1, "emission Samples" should be changed to --emission samples--

Signed and Sealed this
Eighteenth Day of August, 2015

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office